TRANSITION FROM LOCALIZED IGNITION TO FLAME SPREAD OVER A THIN CELLULOSIC MATERIAL IN MICROGRAVITY

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Introduction

Ignition and flame spread processes are complicated by strong coupling between chemical reactions and transport processes, not only in the gas phase but also in the condensed phase. In most previous studies, ignition and flame spread were studied separately with the result that there has been little understanding of the transition from ignition to flame spread. In fire safety applications this transition is crucial to determine whether a fire will be limited to a localized, temporary burn or whether it will grow to become a large fire. In order to understand the transition to flame spread, the transient mechanisms of ignition and subsequent spread must be studied. However, there have been no definitive experimental or modeling studies because of the complexity of the buoyancy-induced flow near the heated sample surface. One must solve the full Navier-Stokes equations over an extended region to represent accurately the highly unstable buoyant plume and entrainment of surrounding gas. To avoid the complicated nature of the plume problem under normal gravity, previous detailed radiative ignition models were assumed to be one-dimensional [1] or were applied at a stagnation point [2]. Unfortunately, these models could not be extended to include the transition to flame spread.

To overcome the above difficulty, theoretical results obtained without buoyancy can be directly compared with experimental data measured in a microgravity environment. Thus, the objective of this study is to develop a theoretical model for ignition and the transition to flame spread and to make predictions using the thermal and chemical characteristics of a thermally thin cellulosic sheet which is used as a sample fuel. This sheet can ignite without requiring a pilot flame and exhibit significant flame spread during test times available in NASA's drop towers or in the space shuttle. The fact that no pilot flame is required eliminates many complicating parameters such as the flame location, temperature, and size [3].

Theoretical Model

Gas Phase: The absence of gravity (microgravity is approximated to be zero gravity) removes the buoyancy-induced vorticity generation mechanism. The small scale of the planned experiment, together with the slow external flow (less than 10 cm/s, simulating the ventilation flow level in a spacecraft) implies a low Reynolds number flow domain. When surface pyrolysis is present, the thermally-induced surface blowing velocity must be taken into account, even at low Reynolds numbers. Both these concepts can be accommodated by assuming the velocity field to be a potential flow [4]. The only loss is the no-slip boundary condition which is already relaxed in the classical Oseen approximation to low Reynolds number phenomena. This approximation is adopted and is implicit in the analysis. We assume that the gas phase reaction is represented by a global one step Arrhenius reaction and its kinetic constants are determined experimentally. A time-splitting algorithm is adopted to accommodate the difference in time-scale between the fast gas phase reaction and the relatively slow convection-diffusion processes.

Condensed Phase: It is assumed that the condensed phase consists of a thermally thin sheet of cellulosic material, uniform in composition through its depth. The thermal degradation of the cellulosic sheet is described by two global thermal degradation reactions and a char oxidation reaction [5]. They are:

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(1) an endothermic global pyrolysis reaction which degrades the cellulosic sheet to gases and a char, (2) a weakly exothermic global thermal oxidative reaction which degrades the cellulosic sheet to gases and a char, (3) a highly exothermic global char oxidation reaction which degrades the char to gases and ash. The gases are characterized as either combustible or non-combustible, the former consisting of hydrocarbons and CO; the latter consisting of CO_2 and H_2O. It is assumed that the combustible gases formed from each reaction above are the same. Although these reactions are crudely approximated compared with the extremely complex degradation reactions, their accuracy is comparable to the one-step gas phase oxidation reaction for the combustible gases. Values for the kinetic parameters of the three degradation reactions, along with the heats of reaction for a cellulosic paper, have been measured; the details are given in Ref. [5].

Results and Discussion

Calculations have been performed for both a two-dimensional, axisymmetric configuration and a three-dimensional, Cartesian configuration, which includes an imposed wind. A schematic diagram of the ignition and transition to flame spread for the three-dimensional case is shown in Fig. 1. External radiation with a Gaussian distribution (a peak flux of 5 W/cm^2) continuously heats a small surface area (about 1 cm diameter) of an infinite extent of the thin paper. Due to the lack of gravitational force, the flow field is assumed to be the same on each side of the sample surface. We also assume symmetry about the plane which is perpendicular to the sample surface and parallel to the direction of the imposed wind. These assumptions allow for computations with spatial resolution on the order of a millimeter.

In the quiescent, axisymmetric configuration, calculations were made in atmospheres of 21%, 30% and 50% oxygen concentrations (mole fraction). The 3D calculation was made with an imposed wind of 5 cm/s in an atmosphere of 50% oxygen. Ignition is achieved at about 0.6 s after the initiation of irradiation, which is slightly later than that in a quiescent condition. This is the result of a slightly lower gas phase temperature near the irradiated area due to the imposed flow. A nearly spherical flow field is generated by the expansion of the gas due to the addition of heat from the exothermic gas phase reaction and the addition of the degradation products from the condensed phase. The gas phase temperature distribution at 0.65 s is shown in Fig. 2. It is skewed toward the downstream by the external flow. The peak gas phase temperature is about 2400°K. The nearly spherical flow field relative to the external flow disappears rapidly followed by a complex flow field mainly controlled by the addition of the degradation products. After the center part of the sample is consumed, the region of degradation moves outward. The temperature distribution after 1.10 s is shown in Fig. 3. The flame spreads upstream at about a rate of 1 cm/s, but it is not clear whether the other part of the flame spreads downstream. However, the results show clearly that the downstream part of the flame is much weaker than that of the upstream part of the flame. This trend is reflected in the temperature distribution at 1.10 s, where the normal temperature gradient at the upstream part of the sample surface is larger than the temperature gradient at the downstream part. A similar trend was observed in a recent study of Olson of a bi-directional, two-dimensional flame spread with a wind [6].

The distribution of external, radiative and convective/conductive energy feedback to the sample surface along the centerline at 0.65 and 1.10 s is shown in Fig. 4. The peak energy feedback rate for the upstream part of the flame increases rapidly up to about 2.0 W/cm^2 after 0.6s and remains at this value. However, the peak rate for the downstream part of the flame increases to about 1.5 W/cm^2 at 0.7 s and gradually its value decreases, although the positive energy feedback region extends downstream. These peak values are much less than the 6 W/cm^2 calculated in the quiescent case.

Acknowledgement

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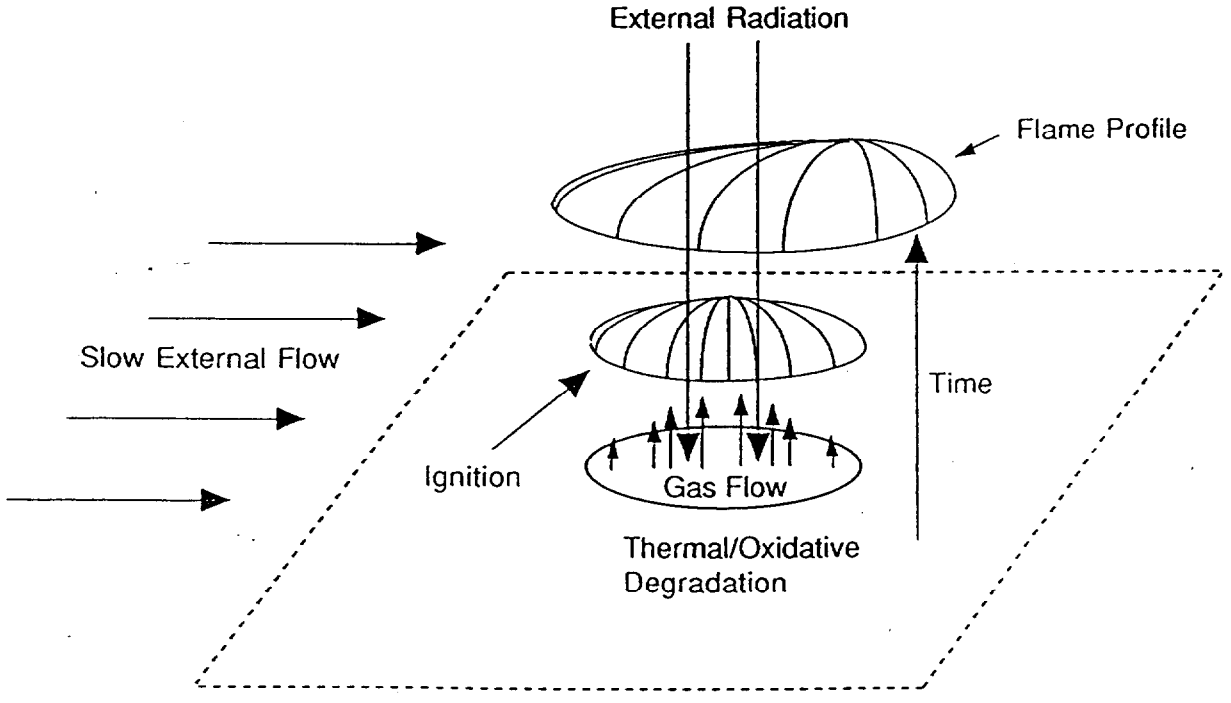

Figure 1: Schematic diagram of the radiative ignition process.

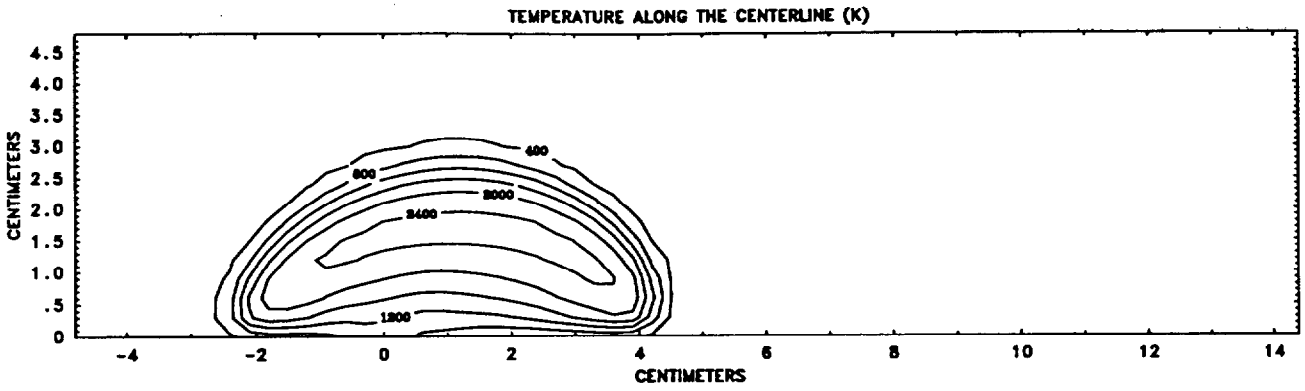

Figure 2: Temperature profile of the flame along the centerline 0.65 seconds after the initiation of the external radiative heat flux, which is centered at the point $x = 0$.

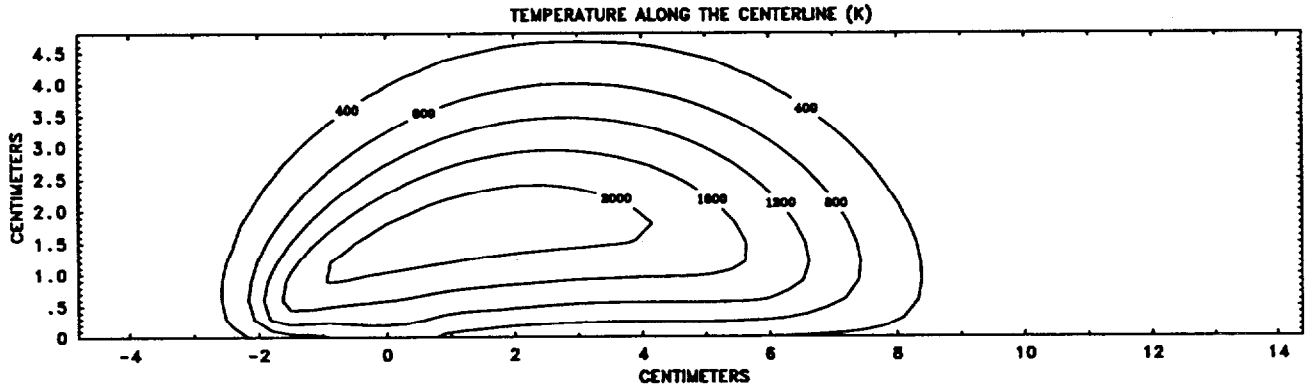

Figure 3: Temperature profile of the flame along the centerline after 1.10 seconds. Note the steeper temperature gradient at the upstream part of the sample surface.

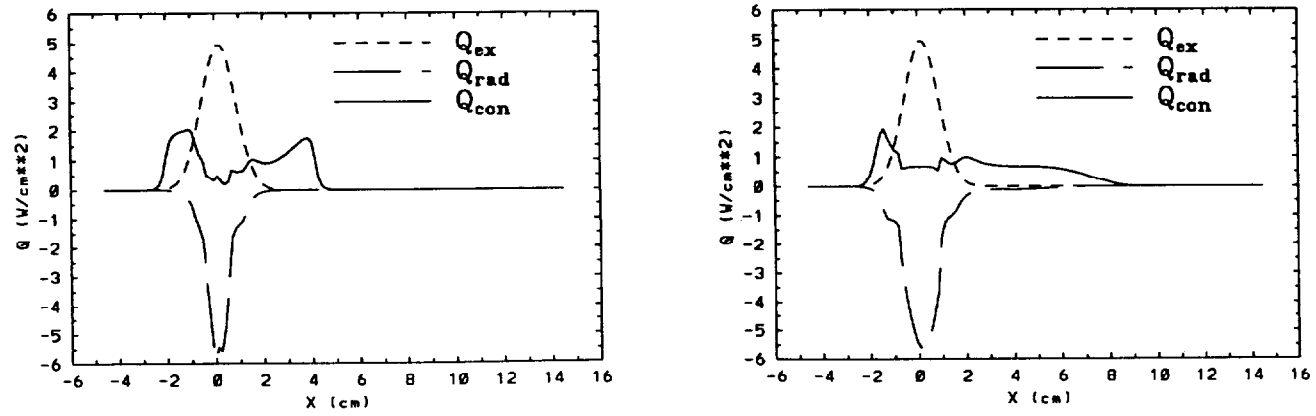

Figure 4: Heat fluxes at the sample surface along the centerline due to the external radiative flux Q_{ex}, radiative loss from the sample Q_{rad}, and convective feedback from the gas phase reaction Q_{con}. The plot on the left is after 0.65 seconds, the plot on the right is after 1.10 seconds.